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OPPO: An optimal copy allocation scheme in mobile opportunistic networks

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Abstract Mobile Opportunistic Networks (MONs) use the store-carry-and-forward scheme to transmit packets, so as to deal with the intermittently connected links. This new communication paradigm makes them very different from the traditional multi-hop wireless networks. To improve the delivery performance, some smart forwarding schemes have been proposed by injecting multiple copies of packets into the temporal network. Unfortunately, these schemes allocate data copies following the aggregate contact information, i.e., information obtained by considering the samples from all pairs. They ignore the individual contact feature of nodes. We show that the aggregate contact can be very different from the contact of individual pairs, therefore, using the former to guide copy allocation is not correct in general, although it works well in some cases. In this paper, we propose OPPO, an *op*timal co*p*y all*o*cation scheme in MONs. OPPO exploits the transient contact ratio of nodes to spray data copies. Theoretical analysis proves that OPPO achieves the optimal delivery delay, and experimental results verify it simultaneously improves the packet delivery ratio compared to the SprayWait and HS, two state-of-the-art works.

Keywords Data forwarding · Copy spraying · Individual contact · Mobile opportunistic networks

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1 Introduction

With recent progress in sensing and wireless communication technologies, current portable devices such as smart phones, tablets and laptops have powerful capabilities especially in sensing, computing and communication, which triggers research in leveraging them to collect data from physical world or share interests among communities. Such sensing/communicaton paradigm is generally called mobile opportunistic networks (MONs) [1]. Compared to the traditional wireless multi-hop networks (e.g., ad hoc sensor networks), one of the most distinct characteristics of MONs is that the connectivity is intermittent. This feature makes them suitable for scenarios with temporal topology, and enables numerous applications ranging from wild monitoring [2–4] to crowd sensing [5–7], from rural communications [8–10] to metropolitan awareness of issues [11–13], etc.

Due to the node mobility and intermittently connected links, data forwarding is an important but challenging problem in the above scenarios. To improve the delivery performance, most of data forwarding algorithms employed multiple copies of packets. These schemes can be generally divided into two categories based on the number of copies they used. One is non-quantitative scheme, where the number of copies is unlimited. This scheme focuses on how to select qualified relays with high probabilities to meet the destination, the classical works mainly include PROPHET [14], BUBBLE [15], SMART [16] and Hotent [17] etc. The other is quota-based scheme, where the number of copies is determined in advance.Different from the relay selection problem in the non-quantitative scheme, the key issue in the latter is that how to allocate copies effectively and

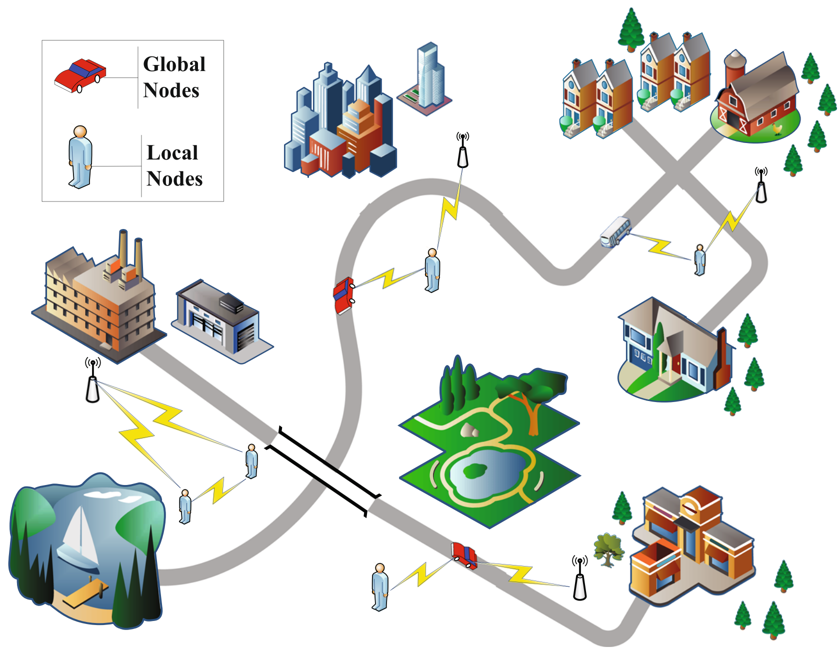


Fig. 1 A mobile opportunistic scenario

efficiently. SprayWait [18] and its variants [19–22] use a binary diffusing method to allocate copies, which achieves a better performance if the movement pattern of nodes is independent and identical distribution. Other protocols like Hug [23], HS [24] and employ additional static nodes in communities to spread messages.

We notice that the aforementioned algorithms distribute copies of packets with node's aggregate contact information but neglect the individual contact feature, making them less efficient. This is mainly because node's contact ratio[1] is temporal even in a homogenous scenario, let alone a scenario where nodes have different mobility patterns. As shown in Fig. 1, people and vehicles with smart devices form a mobile opportunistic network to exchange messages and share local interests. The mobility of the two kinds of nodes is obviously different. Vehicles have a global mobility since buses and cars travel around a city, in contrast, people always wander around several communities where they lived, they hence follow a local mobility.

Motivated by these facts, this paper proposes OPPO, a novel copy allocation scheme in MONs. OPPO integrates the individual contact ratio and uses it as heuristic information to spray data copies. When two nodes have a contact, the number of copies they carry is proportional to their own contact ratios. We summarize our contributions as follows:

– We observe that the aggregate contact ratio of nodes is different from the individual one even in a homogeneous environment and analyze the influence of this feature on copy allocation scheme in MONs.
– We theoretically evaluate HS and Hug and show that good performance is achieved only for a relatively narrow range, beyond which the SprayWait achieves the suggested performance.
– We prove OPPO achieves the optimal delivery delay both in homogeneous and heterogeneous scenarios. We also demonstrate that OPPO improves the packet delivery ratio compared to the SprayWait and HS, two state-of-the-art works.

The rest of this paper is organized as follow. Section 2 introduces the preliminaries. In Section 3.1, we propose the OPPO algorithm and analyze its performance. Section 3.2 presents experimental results. We conclude our paper and discuss some future research areas in Section 4.

2 OPPO: preliminaries

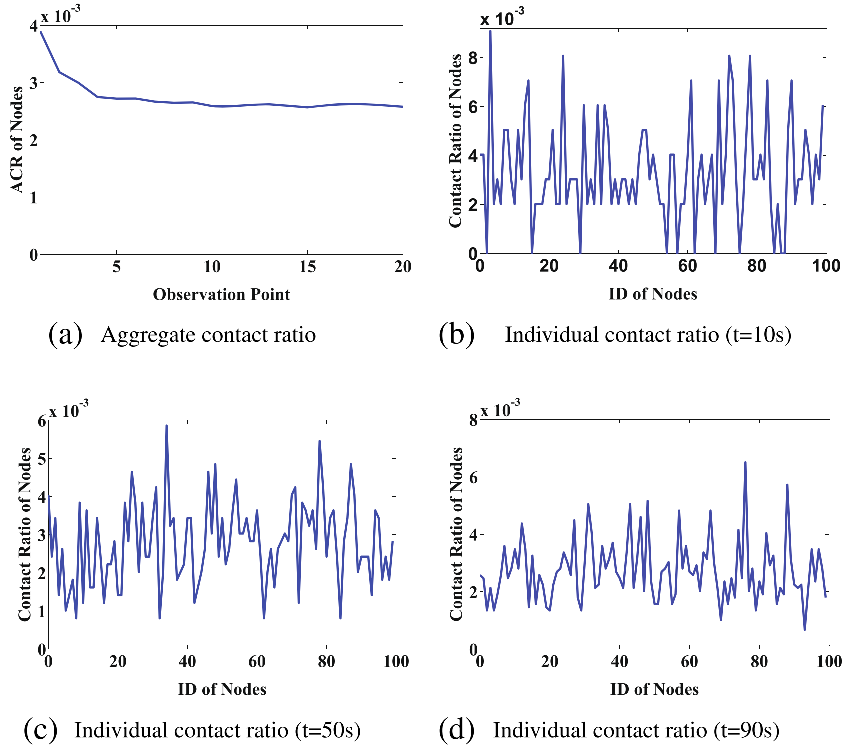
In this section, two classical case-study protocols, SprayWait and HS are discussed, and the difference between the aggregate contact ratio and the individual one is analyzed.

SprayWait [18] distributes copies of packets in a binary way, that is, when two nodes have a contact, the node with K copies allocate half of them to the other without copies. The newly encountered node takes the same way to spray the rest copies until one copy left.

Homing Spread (HS) [24] takes community structures (which are called home) into account. Each home supports a virtual box [25] which has a priority to spread the messages. The mobile nodes including the source dump all copies to the home firstly (*homing phase*), then the home sprays

[1]The contact ratio of a node is the number of contacts between itself and others in one time slot.

Fig. 2 The difference between the aggregate contact ratio and individual contact ratio



one copy to each mobile node located at the same community (*spreading phase*) and the last copy is kept until it is fetched by the destination node (*fetching phase*).

Clearly, for both SprayWait and HS to function properly, the contact ratio of nodes must be fully understood. We argue that this heavily depends on the scenarios where they run. SprayWait assumes that all nodes follow the same mobility model and visit each location uniformly, hence the contact ratio of each node is almost identical. On the other hand, HS assumes that the home has a higher contact ratio than others, which indicates that it may work well in a heterogenous scenario. Furthermore, both of them allocate copies of packets with node's aggregate contact information and neglect the individual contact feature. We notice that node's individual contact ratio is very different from the aggregate one even in a homogenous scenario. That is, the aggregate contact ratio generally follows exponential distribution while the individual one follows Pareto distributions. Besides, the exponential cutoff will emerge [26] if the average inter-contact times of individual pairs are limited. We test this using a community mobility model adopted by HS and PROPHET.

Figure 2 shows the difference between the aggregate contact ratio (ACR) and the individual contact ratio. In order to observe the aggregate contact ratio of nodes, we set 20 observation time points evenly in the simulation process (for the experimental settings, please refer to the Section 3. B). At each observation point, we first compute the accumulative contact ratio of each node and then average all pairs. The results are shown in Fig. 2a, we observe that after a short start phase, the curve tends to be smooth and steady, which means that each node has the similar ACR. We simultaneously demonstrate that the individual contact ratio of nodes is significantly different from the ACR as shown in Fig. 2b, c, d, where we record the individual contact ratio of nodes at the moment $t = 10$, 50 and 90 seconds, respectively. We can see that each node has different contact ratio at the same moment, and the maximum is even reach up to 8 times of the minimum.

Note that the key point of opportunistic routing protocols is that a node should decide whether to spray a copy to encounter nodes or not. The forwarding process tends to be random if we use the aggregate contact ratio, this is mainly because each node has the same/similar metric, which degenerates the performance of data forwarding. On the contrary, nodes have different individual contact ratios as shown in the Fig. 2b–d, which helps them to select relays.

3 OPPO algorithm

Motivated by this heuristic information, we design the OPPO algorithm by taking the individual contact ratio between node pair into account. In the copy allocation phase, every packet and its $K-1$ copies are disseminated by the source node and possibly other nodes carrying more than one copy to K distinct relays. For any node I with l copies $(1 < l < K)$, when it encounters one node J without copies,

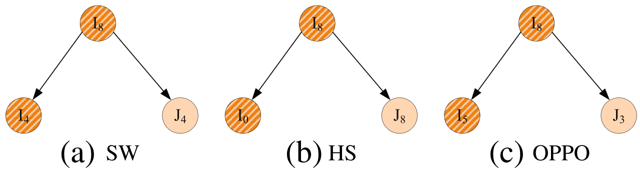


Fig. 3 The copy spraying process between two nodes under three different protocols

it forwards $\lfloor l\beta_j/(\beta_i+\beta_j)\rfloor$ copies to the node J and keeps $\lceil l\beta_i/(\beta_i+\beta_j)\rceil$ for itself,[2] where β_i is the contact rate of node I in time t, so does the β_j. Obviously, the way to allocate copies is only based on nodes' contact ratios and independent of concrete scenarios. When $\beta_i = \beta_j$, OPPO allocates copies in a binary way, and when $\beta_i << \beta_j$, node I dumps all copies to node J, i.e., OPPO provides a more general way to allocate copies, in this way, SprayWait and HS are two special samples of OPPO.

Figure 3 demonstrates the difference among the three protocols, where the subscripts indicates the number of copies nodes carry. Assume that node I initially carries 8 copies. Figure 3a shows the allocation process of SprayWait, since it takes a binary way, both node I and node J will get 4 copies after the spraying process. In Fig. 3b, suppose node J is a homing node, node I will deliver all the copies to it according to the HS. Figure 3c shows the copy spraying process of OPPO, which distributes copies in proportion to nodes' contact ratio, so node I will spray 3 copies to node J and keeps 5 copies for itself (suppose that $\beta_i = 0.5$ and $\beta_j = 0.3$).

3.1 Performance analysis

In this section, we discuss the performance of HS, SprayWait and OPPO. We first analyze the critical condition with which the HS algorithm can achieve the suggested performance.

3.1.1 Critical conditions of HS

HS exploits additional static nodes placed in each community to allocate data copies. The main reason behind this scheme is that the contact ratio of static nodes is supposed to be higher than that of mobile nodes. The copies hence can be quickly disseminated. Let D_h and D_s denote the packet delivery delay of HS and SprayWait, respectively. Let β denote the contact ratio of mobile nodes, and γ denote the contact ratio of static nodes (we can estimate the two values under given mobile models [18]). We have the following lemma:

[2]When two nodes have a contact, they first swap their contact ratios.

Lemma 1 *HS achieves the suggested performance (i.e., $D_h \le D_s$), if and only if $\frac{\beta}{\gamma} \le \frac{\log(l)}{l}(1 \le l \le K)$.*

Proof Let us focus on the delay in wait phase (i.e., K copies of a packet m have been allocated). Both algorithms achieve the same delivery delay if the static node does not carry a copy; on the other hand, if the static node carries one copy, the delivery delay of HS is lower than SprayWait in the wait phase, this is mainly because the static node has a bigger chance to encounter the destination node, and for the other $K-1$ copies, the probability meeting the destination node under the two protocols is identical since they are carried by $K-1$ mobile nodes. Integrating the two situations, we get $D_h \le D_s$ in wait phase.

Next we discuss the delivery delay in spray phase. Suppose that the static node needs to allocate l copies, it spends l/γ (because it needs to wait $1/\gamma$ to encounter other nodes and each time the static node sprays one copy to the newly encountered node). Now assuming that one mobile node carries the same l copies, it at least needs $log(l)$ moments to disseminate the $l-1$ copies (note that the quickest method to distribute copy for mobile node is the binary way [18]), the delay is therefore $log(l)/\beta$. So the delivery delay of HS is lower than that of SprayWait when $l/\gamma \le log(l)/\beta$. After a simple algebra, we get the conclusion.[3] □

3.1.2 OPPO achieves the optimal delivery performance

OPPO allocates data copies in a proportional way, that is, the number of copies one node carries is just based on its individual contact ratio. We hence wonder whether nodes with high contact ratios or those with low contact ratios play a big role in delivery delay. We have the following lemma (the proof can be found in appendix).

Lemma 2 *For any node I and J, let D_i and D_j denote the forwarding delay of node I and J, respectively. If $\beta_i \ge \beta_j$, we have $D_i \ge D_j$.*

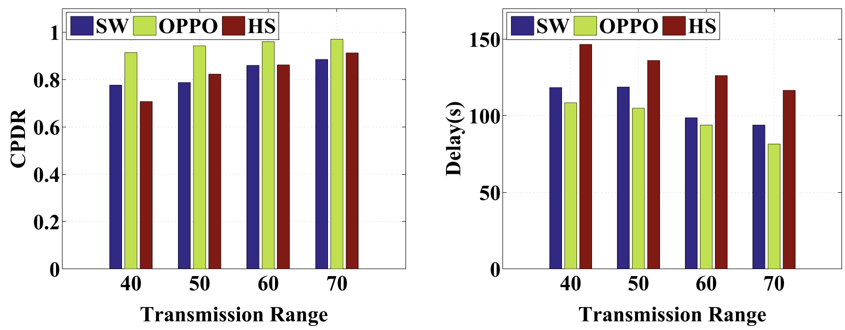
Proof For node I with l copies, suppose that after x times, node I sprays $l-1$ copies, we have:

$$l\left(\frac{\beta_i}{\beta_i+\beta_j}\right)^x = 1$$

Since $1/\beta_i$ is the inter-contact-time between node I and other nodes, we have:

$$-D_i = \frac{1}{\beta_i} \times x = \frac{1}{\beta_i} \log_{\frac{\beta_i}{\beta_i}+\beta_j} \frac{1}{l}$$

[3]Note that Hug uses the similar forwarding scheme as HS (please refer to the introduction section), the aforementioned condition is also fit for Hug.



(a) CPDR (b) MDD

Fig. 4 The CPDR and MDD in different Transmission Ranges

Similarly, for node J, we get $D_j = \frac{1}{\beta_j} \log_{\frac{\beta_j}{\beta_i+\beta_j}} \frac{1}{l}$.

Integrating the two formulas, we have:

$$\begin{cases} D_i = \frac{1}{\beta_i} \log_{\frac{\beta_i}{\beta_i+\beta_j}} \frac{1}{l} = \frac{1}{\beta_i} \frac{\lg l}{\lg(1+\frac{\beta_j}{\beta_i})} \\ D_j = \frac{1}{\beta_j} \log_{\frac{\beta_j}{\beta_i+\beta_j}} \frac{1}{l} = \frac{1}{\beta_j} \frac{\lg l}{\lg(1+\frac{\beta_i}{\beta_j})} \end{cases}$$

Since we try to prove $D_i \geq D_j$, the problem is equivalent to be:

$$\frac{1}{\beta_i} \frac{\lg l}{\lg(1+\frac{\beta_j}{\beta_i})} \geq \frac{1}{\beta_j} \frac{\lg l}{\lg(1+\frac{\beta_i}{\beta_j})}$$

Let $\beta_i = c\beta_j$ ($c > 1$, recall that $\beta_i > \beta_j$). After some algebras, we get:

$$\frac{1}{c} \frac{1}{\lg(1+1/c)} \geq \frac{1}{\lg(1+c)}$$

which is equal to:

$$(1+\frac{1}{c})^c \leq 1+c$$

When $c \geq 2$, the above result holds. □

Lemma 2 illustrates the fact that delivery delay of OPPO is mainly determined by nodes with high contact ratios. In other words, these nodes tend to "attract copies" and carry copies for a longer time than those with low contact ratios.

We now compare the performance of OPPO with SprayWait. For SprayWait, the delivery delay mainly depends on the lower contact ratio nodes due to the binary spraying way. Let D_o denote delivery delay of OPPO, we have:

Theorem 1 *OPPO achieves the better delivery performance than SprayWait.*

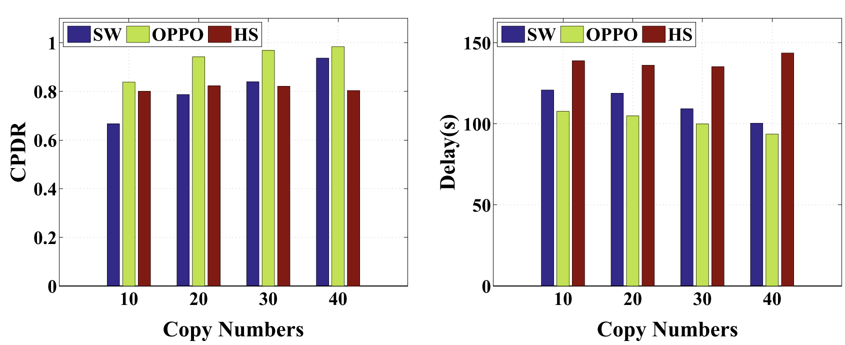
Proof In wait phase, K nodes with higher contact ratios carry the K copies in OPPO, while SprayWait does not take the contact ratio into account and sprays copies randomly (i.e., the number of copies one node carries is independent of its contact ratio). So OPPO can fast deliver packets to destinations.

We next focus on the delivery delay in spray phase. From *lemma 2*, we know nodes with higher contact ratio are the key factor of OPPO in this phase, so do the lower ones of SprayWait. We have:

$$\begin{cases} D_o = \frac{1}{\beta_i} \log_{\frac{\beta_i}{\beta_i+\beta_j}} \frac{1}{l} \\ D_s = \frac{1}{\beta_j} \log \frac{l}{2} \end{cases}$$

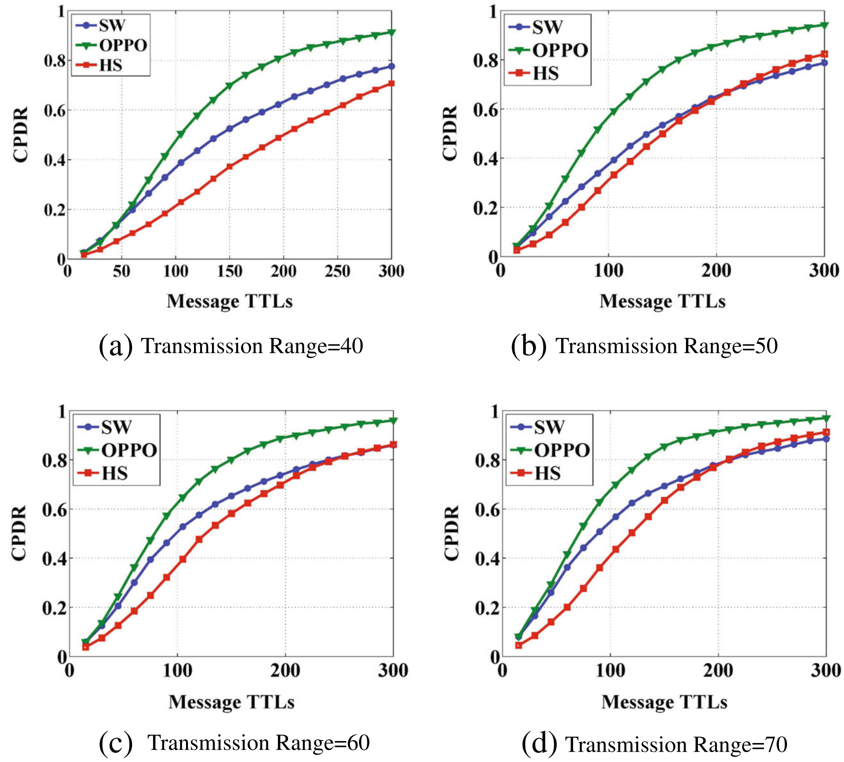
Similarly, suppose $\beta_i = c\beta_j$ ($c \geq 1$), we get:

$$\begin{cases} D_o = \frac{1}{c\beta_j} \log_{\frac{c}{1+c}} \frac{1}{l} = \frac{1}{\beta_j} \frac{lgl}{lg(1+1/c)^c} \\ D_s = \frac{1}{\beta_j} \log \frac{l}{2} = \frac{1}{\beta_j} (\frac{lgl - lg2}{lg2}) \end{cases}$$



(a) CPDR (b) MDD

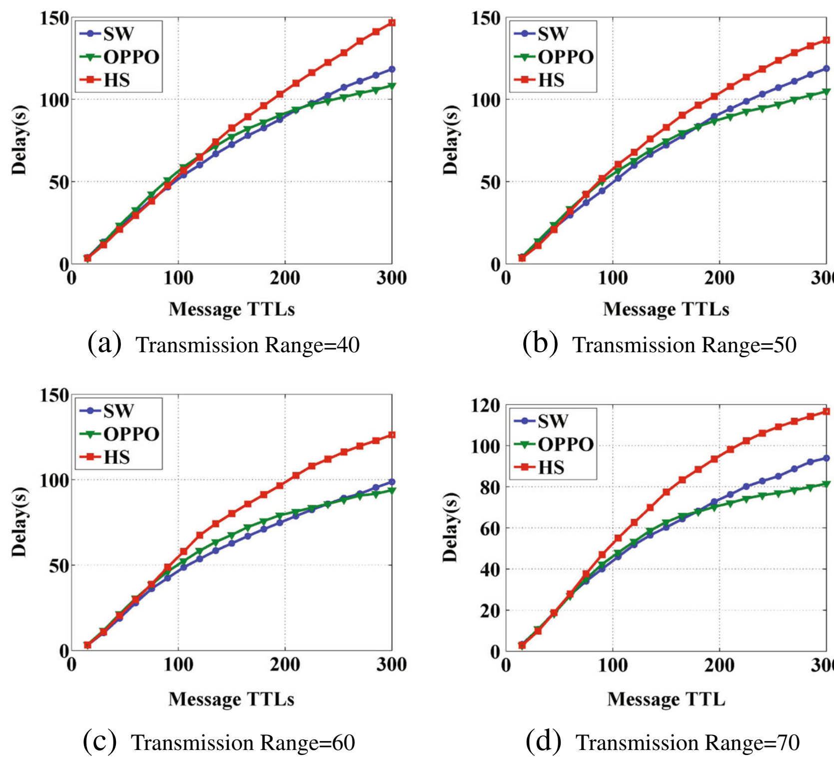
Fig. 5 The CPDR and MDD in different Copy Numbers



(a) Transmission Range=40 (b) Transmission Range=50

(c) Transmission Range=60 (d) Transmission Range=70

Fig. 6 The CPDR of different Transmission Range under Message TTLs



(a) Transmission Range=40 (b) Transmission Range=50

(c) Transmission Range=60 (d) Transmission Range=70

Fig. 7 The Delay of different Transmission Range under Message TTLs

Because $(1+\frac{1}{c})^c \geq 2$ when $l \gg 2$, we get:

$$\frac{lgl}{lg(1+\frac{1}{c})^c} \leq \frac{lgl}{lg2} - 1$$

So $D_o \leq D_s$. That is to say, the delay of OPPO is less than that of SprayWait in spray phase. Integrating both the wait and spray phase, we get the conclusion. □

Note that we can get the same conclusion by analyzing node J if $\beta_i \leq \beta_j$. We next demonstrate the optimal performance of OPPO. Suppose that there exists another copy allocation scheme, which allocates more copies to nodes with lower contact ratio (e.g., a node J). OPPO will achieve a faster distribution speed than the reference scheme since the same node J will carry less copies in OPPO.

3.2 Performance evaluation

We evaluate the performance of OPPO with SprayWait and HS, which is the latest variant of SprayWait. We implement the community mobility model (CMM)[4] and the simulation area is $600m \times 600m$, which is divided into 25 sub-communities. The number of nodes is 200 and that of data copy is 20. The simulation time is $300s$ and the results are the average values over 100 simulation times. The performance metrics include the cumulative packet delivery ratio (CPDR) and mean delivery delay (MDD). Other parameters of CMM keep the default values as in [14].

Figure 4 shows the results under different transmission range, where the term "SW" denotes SprayWait. It's obvious to see that OPPO achieves the highest CPDR and the shortest MDD compared to HS and SprayWait. For example, when the transmission range is $40m$, the CPDR of OPPO reaches 91.4 %, while SprayWait is 77.6 % and HS is 70.7 %. The MDD of OPPO is $108.5s$, while SprayWait is $118.3s$ and HS is $146.5s$, OPPO reduces the transmission delay about by 18 % and 46 %, respectively.

Figure 5 demonstrates the results with different copy numbers. We notice that OPPO still achieves the best performance. Compared to another two protocols, OPPO improves CPDR by nearly 20 % compared to SprayWait (k=10). Meanwhile, it decreases the MDD about 13 % compared to SprayWait and 26 % to HS, respectively.

Figures 6 and 7 demonstrate the CPDR and Delay of the three protocols under different message TTLs (copy number=20), respectively. It is obvious to see that OPPO still achieves the highest CPDR and the shortest Delay. For example, the CPDR of OPPO in Fig. 6b is almost 92.5 %, while SprayWait is 79.2 % and HS is 81.1 %. Simultaneously, the delay of OPPO is $106.4s$, and that of SprayWait is $119.5s$, HS is $141.3s$ as shown in Fig. 7b.

[4]Note that CMM is used in PROPHET, Hug and HS, so as to make a fair comparison, we here use the CMM to simulate nodes' movement patterns.

4 Conclusion

In this paper, we propose an optimal copy allocation scheme, called OPPO, to improve the performance of mobile opportunistic networks. We exploit the individual contact feature to design utility function. We prove and show the performance gain from both the theoretical analysis and experimental evaluation. In the future, we will implement OPPO into vehicle scenarios, where the network performance can be improved by offloading the video copies to the road units. Furthermore, extensive simulations under various scenarios will be run to evaluate the protocol, and to explore the influence of different parameter settings and forwarding metrics.

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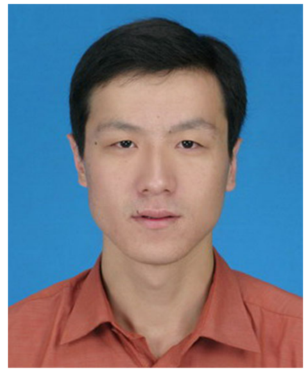

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